Concepts for Mars On-Orbit Robotic Sample Capture and Transfer

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Abstract—**A potential Mars Sample Return (MSR) mission could require robotic autonomous capture and manipulation of an Orbital Sample (OS) before returning the samples to Earth. In one scenario, an orbiter would capture the OS, manipulate to a preferential orientation, transition it through the steps required to break-the-chain with Mars, stowing it in a containment vessel or an Earth Entry Vehicle (EEV) and providing redundant containment to the OS (for example by closing and sealing the lid of the EEV). In this paper, we discuss the trade-space of concepts generated for both the individual aspects of capture and manipulation of the OS, as well as concepts for the end-to-end system. Notably, we discuss concepts for OS capture, manipulation of the OS to orient it to a preferred configuration, and steps for transitioning the OS between different stages of manipulation, ultimately securing it in a containment vessel or Earth Entry Vehicle.**

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1. INTRODUCTION

A potential Mars Sample Return (MSR) architecture consists of a multiphase mission which would incorporate several critical technologies; see [1-4]. The fundamental objective would be to return samples of Martian rock, regolith, and atmosphere for analysis in a terrestrial laboratory. JPL's Mars 2020 Rover will obtain samples and insert them into sample tubes. These tubes will be left on or just beneath the surface of Mars. A future mission could collect the sample tubes on the Martian surface and load them into a Mars Ascent Vehicle (MAV), a small two or three stage solid rocket booster. The MAV would ascend into low Martian orbit (LMO). Once in orbit, the MAV would eject the sample canister as an orbital sample (OS). The OS could be captured in LMO by the conceptual Next Mars Orbiter (NEMO), and reoriented from an unknown orientation to a known orientation. The OS would then be sealed in a redundant fashion by a Break-The-Chain (BTC) process in order to comply with planetary protection requirements. After that, the OS would be inserted into an Earth Entry Vehicle (EEV) to bring it back to Earth. This paper specifically addresses the capture, reorientation, and retention of the OS.

2. ORBITING SAMPLE (OS) PARAMETERS

The parameters described next for the OS are notional and consistent with current formulation efforts. These are, however, likely to evolve and change as the MSR mission concept formulation is currently an ongoing effort.

The OS would be captured with an incoming relative speed of up to 10 cm/s, and a rotational speed of up to 10 RPM. The OS would be equipped with a beacon to track its relative location to within 10 cm (including the positional and attitudinal uncertainty of the spacecraft).

The OS would have a mass of 12 kilograms and a major diameter of 28 centimeters, and would be roughly spherical in shape. Because the OS serves as the nose cone of the MAV, one hemisphere of the OS would feature Thermal Protective Shielding (TPS). This hemisphere may not be modified with positive features, but may have negative features e.g. a groove or blind hole. The opposite hemisphere may have either positive or negative features, but would require negative features for the ejection mount on the conceptual MAV. Henceforth the plane dividing these hemispheres will be referred to as the equatorial plane.

The OS would be loaded with the sample tubes such that the tubes are oriented at a 45-degree angle with respect to the equatorial plane.

3. System context

As the distance between the OS and the spacecraft narrows to one meter, the OS would fill the entire field of view of the onboard camera and no new data would be taken. As such, the capture of the OS would have to be completed entirely autonomously, and failure could result in an uncontrolled collision between the OS and the spacecraft. The goal of the capture, therefore, would be to autonomously accommodate the full spectrum of position error and nonzero incident angle of the incoming OS, and constrain the OS about all three translational degrees of freedom. Ensuring a successful capture would require an evaluation of contact dynamics between the OS and the capturing mechanism, e.g. a capture cone.

The OS would be captured with an unknown orientation; the OS would have to be re-oriented to a specific orientation to prepare for a landing event. Note that in a special case where the required orientation of the tubes is orthogonal to the gravity vector at landing, only 1 degree of freedom must be reoriented. In all other cases, 2 DOF of rotation must be reoriented. In all cases the sample tubes could rotate about their cylindrical axis. Because the nominal landing orientation is not finalized, an optimal design will constrain the OS in 2 rotational DOF.

Once the OS is captured and oriented, it would have to be retained such that its 5 DOF positional and attitudinal constraints are maintained throughout the EEV's crash landing on the Earth's surface. The OS would be retained within the BTC seals, and the OS that would return to earth should not include any vestiges of a capture or reorientation process, e.g. actuators.

4. Potential requirements

In this section, we lay out some of the considerations or potential requirements that went into the development of these concepts and constrained the trade space.

The system shall:

(1) Have as few actuators as possible.
(2) Not rely on a particular coefficient of friction between the OS and any component.
(3) Minimize the components that will remain inside the OS container through the earth re-entry and landing phases.
(4) Retain the orientation of the OS during the entire landing event
(5) Behave in a deterministic way, i.e. a pre-determined time-dependent / limited action set will lead to capture, reorientation and retention of the OS (defined time window is related to power resources).
(6) Make as few modifications as possible to the non-TPS (thermal protection shielding) hemisphere of the OS.
(7) Minimize the volume of the OS container used to retain the OS.
(8) Retain the OS with a different mechanical component than the one used to capture the OS (for planetary protection preference).
(9) Ensure that as few components as possible could interact with the OS, and each of them can be ejected after interaction (planetary protection requirements).
(10) Be compatible with the other architectural elements such as the Mars Ascent Vehicle system, elements of the Break-The-Chain (BTC) system, and EEV system.

5. OS Capture system

Our different concepts for capturing the OS can be broadly classified into two groups. The first uses an active capture device such as a multi-DOF robotic arm to capture the OS. The arm could be used to compensate the 6 DOF pose error between the spacecraft and the OS arising from different sources such as sensor error and spacecraft control error. Such a system would have a sensor for guiding an arm to the incoming OS and an end effector capable of latching on to the arm. Figure 1 shows a concept where an arm is used to capture the OS.

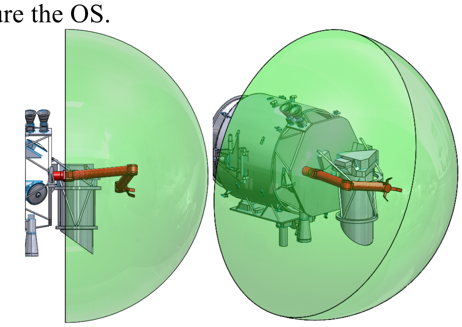

Figure 1. Notional Robotic Arm and End Effector for OS capture, where the green region is the large

workspace offered by the arm

A second approach is predicated on a capture vessel with an actuated lid. The spacecraft would slowly move up to the OS and have the OS enter the vessel. The vessel would be sized to be larger than the three sigma anticipated error between the spacecraft and OS relative position. When the OS is detected to have entered the vessel, an actuated lid would close the opening of the vessel, thereby trapping the OS and capturing it. This approach has been studied and demonstrated in [5] and notionally shown either as a capture cone internal/external to the spacecraft in figure 2.

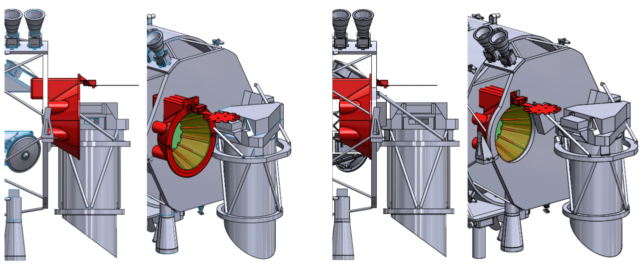

Figure 2. Capture cone with lid integrated external and internal to the spacecraft

Our concepts explored the diversity of the shape and size of this vessel and its lid mechanism. Figure 3 shows a spectrum of lid mechanisms ranging from a rotating disk, an iris mechanism, petal mechanism, and inflatable air bags, among others.

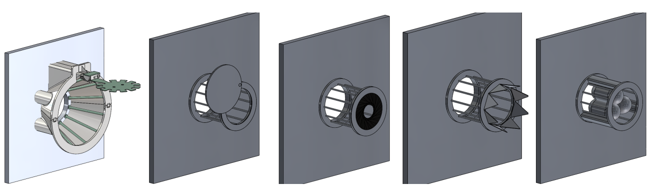

Figure 3. Representative set of different capture lids

We also considered the location of the vessel as a variable, viz. whether it is mounted directly on a spacecraft face (as shown in figure 2) or a boom is used to create some separation between the capture vessel and the spacecraft as shown in figure 4. The boom concept was considered to create separation between any dust emanating from the OS and the spacecraft for benefits to planetary protection requirements.

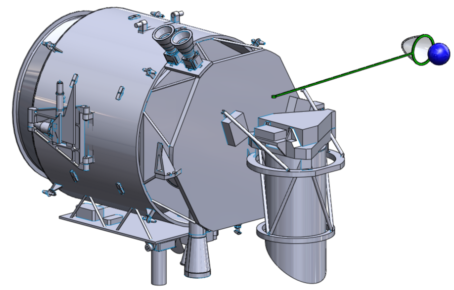

Figure 4. Offset Capture Cone

We also considered a "direct capture" approach where OS could be directly captured in the EEV using an active lid that accounted for the error between the OS and the spacecraft. As shown in figure 5, in this case, the lid would attempt to match the relative velocity of the OS with respect to the spacecraft and cage the OS geometrically before seating it into the EEV.

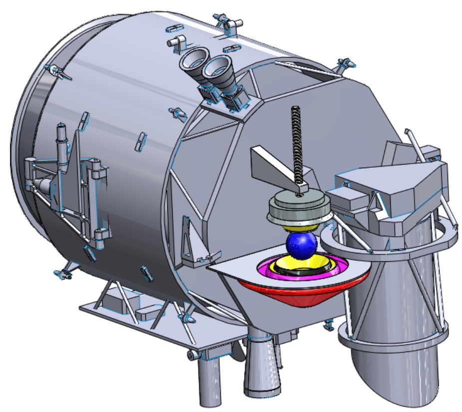

Figure 5. Direct OS Capture Notional Concept

During the capture event, the contact dynamics of the OS making contact with the capture vessel can result in a number of different OS trajectories after first contact, some of which result in the OS heading out of the vessel. While a lid mechanism can certainly alleviate or eliminate the risk of the OS bouncing out of the vessel, we identified the following as a discriminant or preference to help prune the concept space: If the OS can be enclosed in a volume with respect to the spacecraft from which it cannot escape before first contact, then the contact dynamics are not a factor for successful capture. If this could be possible, the dynamics of the OS making contact with the spacecraft could be allowed to attenuate slowly without a risk of losing the OS. This would also reduce the possibility of any ejecta from the OS arising from contact dynamics impacting the spacecraft in any volume outside the capture vessel. This could alleviate the potential planetary protection aspects of a potential mission.

6. Initial Reorientation Concepts

The first reorientation concepts we surveyed were extremely general in nature and did not focus on actuation, mechanisms, or system-level integration. This type of trade-space analysis was useful for identifying various distinct methodologies for reorienting a spherical object. Some initial concepts are briefly summarized below with an understanding that these are representative in nature and do not exhaustively represent a full trade space:

Omni drive wheel: The OS is preloaded against omni drive wheels, which rotate the OS until a spring-loaded retention feature seats into a potential well in the OS. As shown in figure 6, the BallIP features [6] a similar usage of multi-axis reorientation from omni drive wheels to balance a counterweight atop a ball.

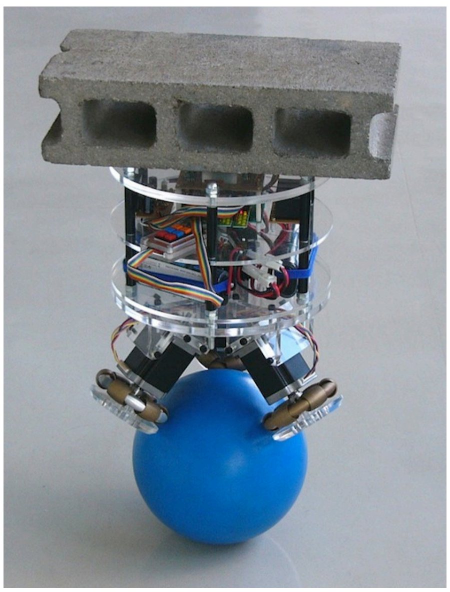

Figure 6. BallIP using omni wheels to balance on a ball

This design uses a gravitational preload to constrain the omni wheels to the sphere; the omni wheels can be constrained to the sphere in a zero g environment by a spring loaded ball transfer.

This design is particularly attractive because it allows the OS to remain fully translationally constrained during reorientation. However, it cannot be considered deterministic because the omni wheels rely on friction to apply a moment to the OS. Because the OS will be dirty when it is reoriented, the coefficient of friction cannot be easily characterized. It is therefore very difficult to determine the required preload to ensure a no-slip condition is met.

Head scratcher: This design utilizes an OS with an equatorial flange. Three “fingers” would start at a single point on the OS (shown in figure 7), and trace three equally-spaced hemispherical paths (shown in figure 8). When the fingers reach a plane, they will each coincide with the equatorial flange.

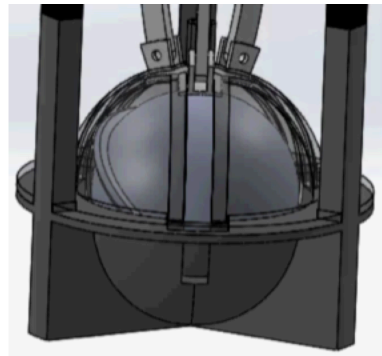

Figure 7. The head scratcher at initial position

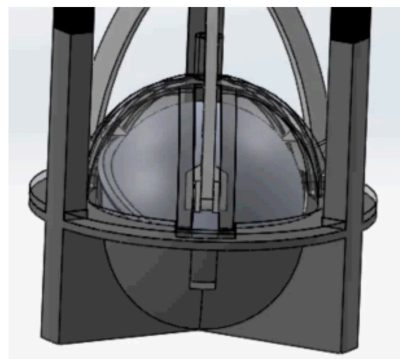

Figure 8. The headscratcher mid operation

This design is highly deterministic, as there is a very small singularity region in which there is a binding potential. By chamfering both the flange and the fingers, the singularity case only exists between a point and a line (the case in which the fingers start exactly on the equatorial plane and never engage with the flange). However, two roadblocks are apparent with this design. The first is that the actual mechanism to move the fingers will be either complicated or bulky. Additionally, the design assumes that the OS will rotate freely but is translationally constrained. Implementing these constraints or accommodating an unconstrained OS adds significant complexity to the design.

Visor: A visor makes a complete sweep around an OS with a pin. The pin is ultimately captured between the visor and a retention feature, with geometric features that direct the pin to a single point. This design will be addressed at length in the ensuing section, *Integrated Engineering Concepts*.

Sense and Constrain: The OS is captured and fully constrained (6 DOF) by a shell on a 2 DOF gimbal. The orientation of the OS is determined via a sensor suite, and the gimbal is rotated to the proper orientation. Here, in place of rotating the OS, the housing shell is rotated on a gimbal using active sensing.

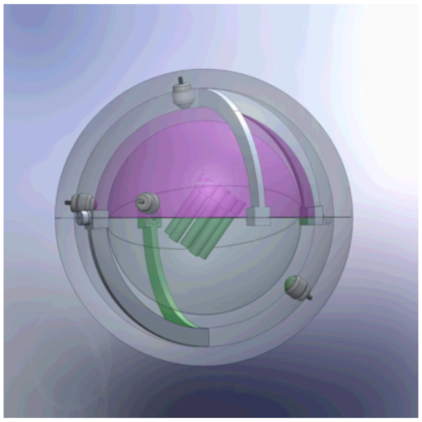

Figure 9. A 2 DOF Gimbal concept

As shown in figure 9, this approach is particularly appealing in the particular case in which the tubes are meant to be oriented perpendicularly to the gravity vector at landing, since the reorientation can be accomplished with a single direct drive actuator. This is especially true since a 2 DOF gimbal complicates any further manipulation of the OS to accommodate BTC operations.
Constraining a spherical OS will rely on friction (i.e. an interference fit) or crushable (i.e. Velcro), unless a retention mechanism can accommodate angular misalignment (e.g. a spring loaded pin engaging against a hole in the OS). Non-frictional retention mechanisms will also require either many parts or many features on the OS so that any OS orientation can engage with the retention mechanism.

Platonic Solid: As a possible solution to the 2 DOF gimbal requiring friction or crushable to retain the OS, we evaluated an OS with a TPS hemisphere and a non-TPS quasi-hemisphere in the form of a platonic solid. Ideally this OS would behave like a sphere during capture, but when the cups, which have mirrored negative features to the platonic solid, fully close they rotate the OS until the faces of the platonic solid seat in the faces of the cups. There are five platonic solids, each with different dihedral angles. This dihedral angle stipulates the maximum reorientation an OS will need to undergo before it seats in the cups. The dihedral angle also determines the moment-arm with which the cup can engage with the OS to reorient it.

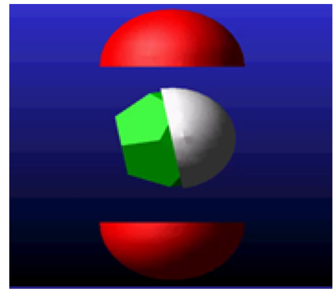

Figure 10. An MSCAdams^{TM} Simulation of the platonic solid concept

As shown in figure 10, we performed several dynamic simulations with MSCAdams^{TM}, and conclude that this working concept presents some problems. While the design works with a low coefficient of friction (~.2), the OS can bind at several initial orientations with a higher coefficient of friction between the OS and the cups. Furthermore, several problems from the 2 DOF gimbal concept persist in this variation. Notably, the 2 DOF gimbal paradigm complicates the ejection of reorientation mechanisms in preparation for the sealing of the OS and loading the OS into the EEV (without including vestiges of the reorientation process).

Iris/Grapple: Inspired by the Canadarm end effector [7] as shown in figure 11, this approach entails closing a grapple or iris around a pin feature on the OS.

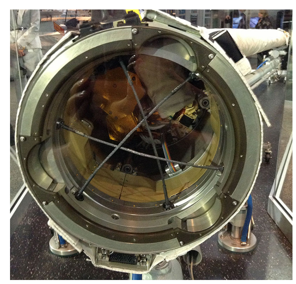

Figure 11. The Canadarm grapple end effector

A grapple would require a free body to have two pins on opposite poles to guarantee a successful reorientation. This poses a problem since requiring pins on both sides of the OS, coincident to the axis of the sample tubes, necessitates a positive feature on the TPS hemisphere of the OS. The need for two pins can be eradicated by spring loading the OS into an opening and closing iris. This, however, features many moving parts. Furthermore, irises are not designed to handle thrust loads.

Trackball: Inspired by a computer mouse, this approach entails actuating a spherical wheel preloaded into the OS until a potential well on the OS aligns with the sphere. As shown in figure 12, this concept is canonically similar to the omni-drive wheel, and therefore faces the same shortcomings.

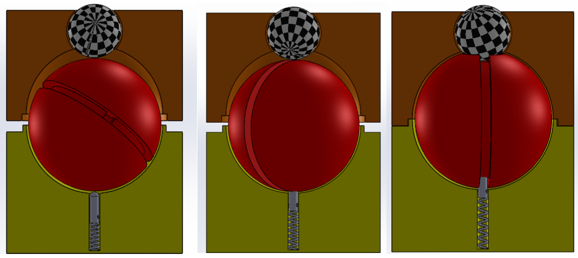

Figure 12. The trackball concept in initial, intermediate, and final states

Nested cone: This design would utilize an OS with pins at both poles. A series of concentric cylinders would engage with the OS, each with a successively larger diameter. As shown in figure 13, each cylinder would preclude the OS from a new range of orientations via the chamfered features. When all cylinders are engaged with the OS, its polar axis is constrained to a plane.

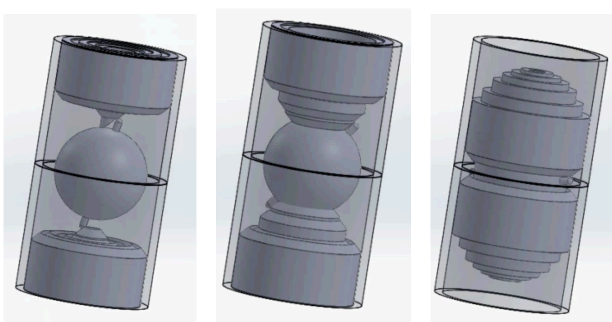

Figure 13. The nested cone concept in initial, intermediate, and final states

This design features many moving parts, and also requires a pin on both hemispheres of the OS. This leads to only a full 5 DOF constrain with the final DOF being in a binary state with either pole as potential final orientations.

Chamfered cylinder: This design utilizes an OS with two hemispheres of different radii (a TPS hemisphere and a smaller non-TPS hemisphere. As shown in figure 14, the OS enters a capture volume of a chamfered cylinder. This chamfering of this cylinder reflects the geometry of the OS such that there is only one OS orientation in which the lid of the cylinder can seat fully. By intermittently applying various torques to the OS via off-center axial loading, the OS should rotate about all 3 attitudinal DOF. To apply these loads, we consider a single degree of freedom linear actuator with a sprung mass system to apply periodic and eccentric torques to the OS.

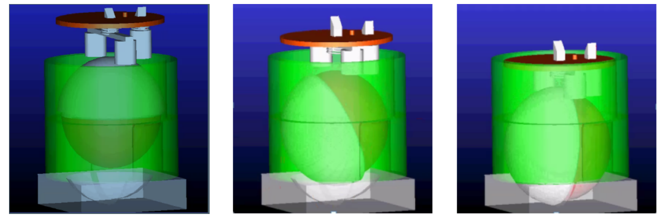

Figure 14. The nominal operation of the chamfered cylinder concept

In this design, we apply this approach twice: the OS is reoriented the first time (passing from ∞^3 to ∞^2 possible orientations), the OS is reoriented the second time (passing from ∞^2 to ∞^1 possible orientations) and then retained using a form closure approach, passing from ∞^1 to the final orientation. This design is non deterministic, and there are several identified singularity cases in which the OS will be unable to reorient.

7. Integrated Engineering Concepts

After considering a number of different stand-alone solutions for capturing the OS and orienting it, some of which are described above, our efforts focused on developing end-to-end concepts for the OS capture, orientation and handling as an integrated system subject to the requirements/preferences described in section 3. While different capture options were pursued, architecturally a cone with a lid stands out as a simple approach and hence our end-to-end concepts all incorporate a “capture cone” for capturing the OS. A potential flight system may look significantly different from representative concepts described below.

Concept 1

This design was developed collaboratively by the authors and JPL’s Atelier study [8] and is summarized here for completeness. As shown in figure 15, this concept uses a capture cone equipped with two sets of actuated blades on either side of the cone and one hemispherical shell of the BTC shells at the smaller end of the cone. Each set of blades consists of a large blade and a small blade, and all four blades are spatially offset. One actuator drives each set of blades.

Figure 15. Concept 1 Capture Phase

The capture phase begins when the OS enters the capture cone. This can be detected either by perception sensors or using dedicated sensors on the capture cone rim such as a set of laser beams that are broken by the incoming OS. When the sensors detect the OS has passed through the opening of the capture cone, the blades are actuated and close in around the OS. The large blades drive the OS towards the center of the cone while the small blades, driven by the same actuator as the large blade, cages the OS by obstructing any feasible path for the OS to bounce out of the cone after first contact with the cone. In nominal performance, the blades close out any egress path of the OS before making contact with the OS, similar in concept to creating a cage around the OS before the OS makes contact with the cone. This ensures that the ensuing OS contact dynamics do not result in any OS trajectory such that the OS can escape the capture cone. The blades are driven until the OS is constrained against the BTC shell at the smaller end of the capture cone and a nominal pre-load is applied to the OS by the arms. At this point, the blades are held in place by brakes and the OS is both captured and constrained – see figure 16. To reduce the OS contact loads with the blade and to damp out the OS contact dynamics, it is advisable to drive the blades with a compliant actuator that could be back driven or potentially series elastic.

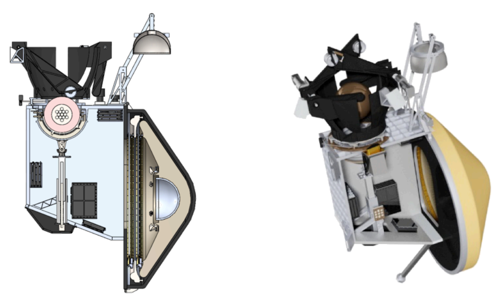

Figure 16. Concept 1 OS Constrained Phase

At the distal end of each large blade, we mount a small, actuated wheel. Due to the spatial offset of the two arms, the wheels make contact on different axes of on the OS. Thus, by rotating the wheels, and through friction drive, the OS can be rotated through a large range of motions. The OS is designed with negative slots and the capture cone is equipped with actuated or sprung pins that can move into these negative slots to retain the OS. As the wheels rotate the OS, these negative slot(s) become aligned with the corresponding pins and the pins retain the OS. Note that for redundancy, one may design more than one pair of negative slot and positive pins. As the OS orientation is dependent on friction, and is not deterministic, the probability of the OS being retained by any one of the pins is higher than the probability of all the pins or any one specific pin retaining the OS. In our design, we used three sets of negative slots and pins such that when any of these pins retained the OS, the desired orientation of the OS was within acceptable limits of the orientation requirements.

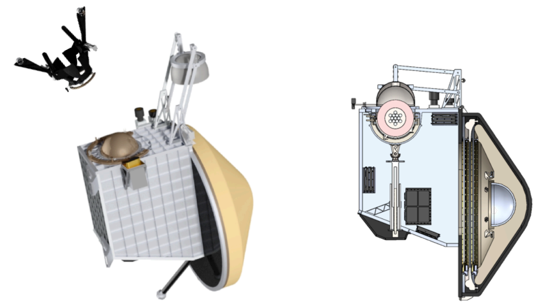

Figure 17. Concept 1 Cone Ejection and BTC shell placement phase

Once the OS is captured, constrained and retained in the BTC shell, the capture cone would be ejected. This would leave the OS in the BTC shell on the spacecraft deck. As shown in figure 17, a separate mechanism would place the other BTC shell on top and subsequent BTC steps (brazing or welding) would be carried out. Concepts for these steps typically include a double-walled shell such that the top or dirty hemisphere remains attached to the spacecraft deck, thereby providing a seal, while the inner shell separates from it to provide a clean surface. As shown in figure 18, the lower BTC shell is mounted on a transfer arm that retracts the OS with its BTC shells from the spacecraft deck, rotates it, and orients it with the EEV. This arm places the OS with its BTC shell in the EEV where it is retained using a similar approach to OS retention. The arm retracts and subsequent steps of BTC containment assurance are undertaken with the EEV lid being closed and EEV ejected from the spacecraft.

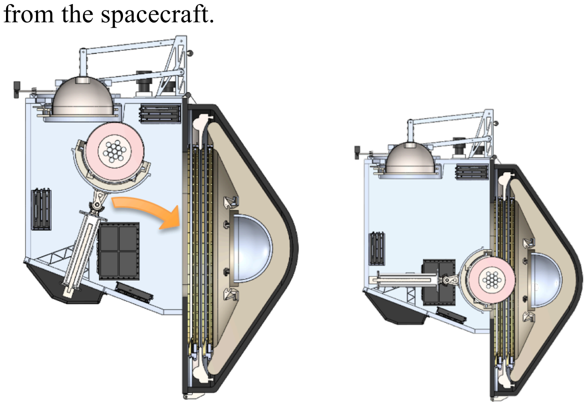

Figure 18. Concept 1 OS transfer phase

The number of actuators used in this design is high and the design depends on frictional drive for orienting the OS, thereby making it a probabilistic approach. Initial computer simulations of the capture phase also identifies cases, particularly those where there is large offset between OS trajectory and the cone axis, where the caging the OS may be difficult or the actuation requirements (speed and torque) may be high. The OS contact impulsive loads on the arm may also be high in certain cases. This makes the actuator design challenging i.e to be sufficiently stiff to prevent OS bounce out yet compliant enough to prevent a high impulsive load on OS contact. The overall design accomplishes all the different steps for the OS capture, orientation, retention and transfer into the EEV. It also provides separation of each step and hence can be verified and validated separately. For example, the capture and orientation steps can be separately tested.

An alternate configuration for this design may be to eliminate the OS transfer aspects and have the OS directly captured into the BTC shell placed in the EEV. Figure 19 shows this configuration.

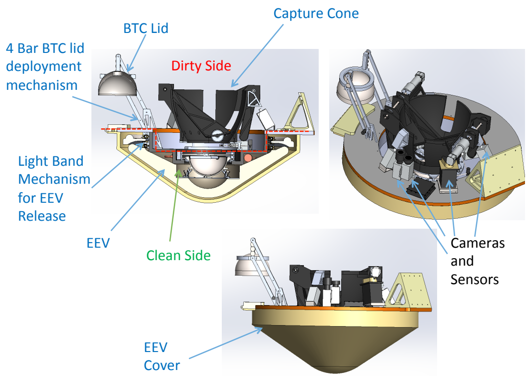

Figure 19. Concept 1 Direct Capture in EEV

CONCEPT 2

This end-to-end design features an OS with an equatorial flange that is simultaneously captured and constrained by two hemispherical BTC shells; the bottom shell is fixed to the base of the capture cone, and the top shell is articulated as the OS is captured as shown in figure 20.

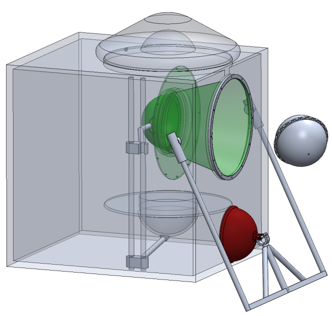

Figure 20. Concept 2 Layout

As the OS entrance in the capture volume is detected similar to concept 1, an actuated pin joint brings the top shell to a position concentric to the bottom shell such that the OS is in between the two shells. The inlet diameter of the cone is sized such that once the top shell has been brought into place the OS is geometrically constrained to the inside of the capture volume as shown in figure 21. This ensures the caging of the OS before it makes contact with the cone.

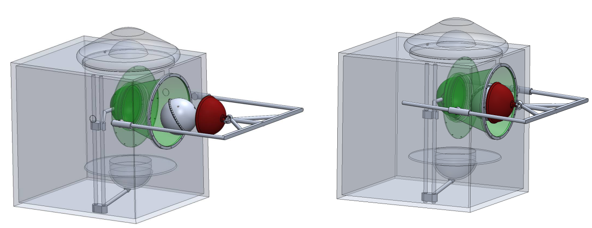

Figure 21. Concept 2 Capture Phase

Once the OS has been constrained to the capture volume, a linear actuator articulates the top shell towards the bottom shell until their flanges are coincident. The inner diameter (ID) of the BTC shells is larger than the outer diameter (OD) of the OS, but smaller than the OD of the flange. Thus the only configuration in which the BTC shells can fully close is the configuration in which the equatorial flange of the OS rests between the two BTC hemispheres (see figure 22). This reorientation paradigm is conceptually analogous to putting a coin on a table: the coin is highly likely to settle in a flat configuration. The singularity-like configuration of the coin settling on its edge can only be satisfied with a narrow range of initial orientations, and can easily be disrupted with small off-radial force. To further reduce the possibility of the OS entering the singularity condition in which the axis of the equatorial flange is clamped normal to the axis of the BTC shell flanges, the flange of the OS is equipped with rollers to minimize friction between the flange and the BTC shells. Furthermore as shown in figure 22, the top lid is attached on a passive universal joint, which is sprung to the neutral position. This joint allows the top lid to deflect in order to more adequately reorient an OS that enters the cone with a trajectory non-coincident to the axis of the cone.

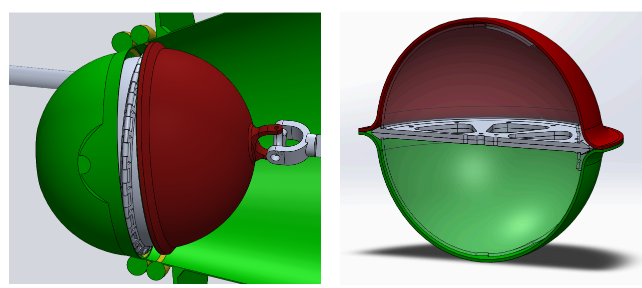

Figure 22. Concept 2 Orientation Phase

Once the flanges of the top and bottom BTC shells have engaged with each other, the OS is fully constrained in 4 degrees of freedom (3 translational and one rotation), constrained to one of two possible configurations in the 5th degree of freedom (depending on which pole of the OS comes in contact with which BTC shell), and unconstrained in the sixth degree of freedom (free to rotate in the polar direction). A need to further constrain the OS is dependent on the orientation of the sample tubes inside the OS with respect to the equatorial flange, as well as the nominal landing orientation of the sample tubes with respect to the EEV. Further reorientation can be implemented by incorporating an orienting feature into the flange of the OS. One implementation would be to incorporate a sprung pin into the top BTC lid, and a clearance hole into the equatorial flange of the OS. Once the BTC shells are closed on each other, the top lid can be rotated about the axis of the cone until the spring pin engages with the negative slot in the equatorial flange of the OS. Once the pin has engaged, the OS will rotate with the top lid and can therefore be rotated to a desired orientation. By rotating the top lid at least one full rotation, the pin will deterministically engage with the OS negative slot before the lid reaches its terminal orientation. Once the OS is fully oriented, the BTC steps of sealing the two shells (brazing, welding or other) can be carried out. The OS with its BTC shells can then be transferred to the EEV in a manner analogous to concept 1 as shown in figure 23. Similarly, the capture cone and the drive mechanism for the capture shell can be ejected, if desired.

The number of actuators in this concept is much lower than the previous one. If appropriately sized, this design provides a large volume in which the OS can be caged in comparison with the previous design. The orientation step is deterministic. Separate steps and mechanisms are not required for OS retention. However, this concept requires a positive feature on the OS in the form of an equatorial ring. This may become inconsistent with other emergent requirements as a potential overall MSR concept is formulated. The steps of capture and orientation are coupled and hence need to be tested together. The OS with its BTC shells may need to be further rotated through 180 degrees if one specific polar orientation is identified as preferential for landing load and sample integrity management. Despite these challenges, this concept too provides all the desired steps, has a smaller number of actuators and all steps are deterministic.

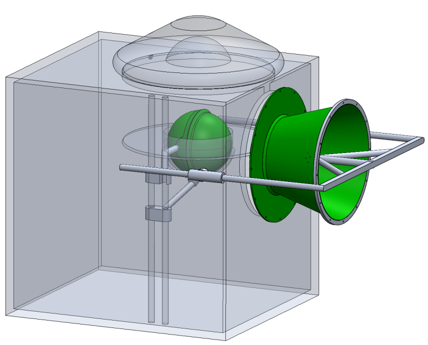

Figure 23. Concept 2 Transfer Phase

CONCEPT 3

Similar to concept 2, this concept also incorporates a capture cone and a BTC hemispherical shell for capture. As shown in figure 24, in this case, the capture cone has a slotted opening for a mechanism to drive the BTC shell into the cone for OS capture and constraint. The capture phase, thus, is similar to concept 2. For orientation, the bottom shell BTC hemisphere is equipped with a set of visors. The visor set is as shown in figure 25 where one of the visors is stationary and the other is rotated by a pin joint and actuator. The visor rotation axis is in the equatorial plane of the BTC shell and as the visor is rotated, it traces a spherical shape inside the shell as shown in figure 26. There is clearance such that the moving visor can trace a full 360 degrees without making contact with the stationary one.

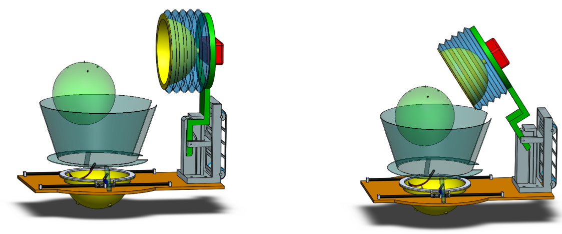

Figure 24. Concept 3 Capture Concept

In this concept, the OS has a positive feature similar to a cylindrical boss on its outer surface. During the capture phase, the two BTC shells are not completed closed but provide just enough clearance such that the OS is enclosed in the locus of the sphere traced by the moving visor. In this configuration, the visor starts to rotate and makes contact with the boss on the OS. It continues to rotate until the boss makes contact with the stationary visor. The OS diameter, boss length, the two visors and the clearance between the two BTC shells are dimensioned such that the rotating visor can trap the boss between itself and the stationary one. Further, the visor shapes are designed such that the continued rotation of the visor causes the boss to slide between the two until it reaches the center of the two visors.

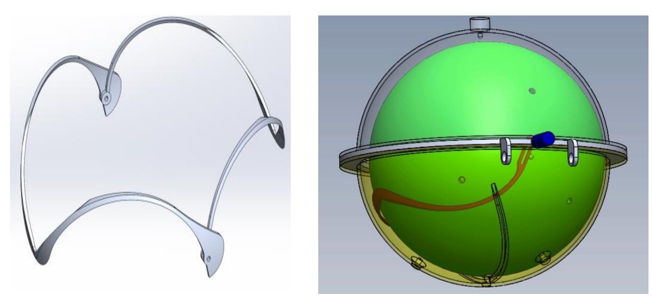

Figure 25. Concept 3 Visor Geometry and Integration in BTC Shells

As shown in figure 25, this corresponds to the most concave aspect of the visor shape. When the OS is in this orientation, i.e. the boss is trapped between the two visors and has slid down to the most concave location on the two visors, it is aligned with a negative slot on the BTC shell. The top BTC shell is pushed down, and in doing so it pushes the OS boss into the negative slot on the BTC shell. The slot incorporates a retention feature and this catches on to the boss on the OS. The OS is now constrained as shown in figure 26.

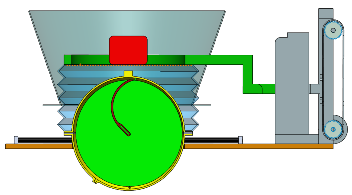

Figure 26. Concept 3 OS Constrained Phase

At this point, the top BTC shell is moved back and the capture cone is ejected as shown in figure 27. The visor mechanism is also ejected as shown in figure 28. It is anticipated that a pyro device such as a frangibolt or a wire-cutter can separate the visor mechanism from the BTC shell. The visor mechanism mounts would be sprung such that the pyro activation would cause the visors to be ejected leaving behind only the OS retained in the BTC shell. The top BTC shell is then brought down and the two BTC shells close until they make annular contact. They are then ready for further BTC steps (e.g. brazing, welding, other options) that seal the two shells together using a double walled shell approach similar to concept 1 and 2. The next steps of transferring the OS with its BTC shells into the EEV are similar to those in concepts 1 and 2.

Similar to concept 2, the number of actuators in this concept is lower than in concept 1. The orientation process is deterministic as one full rotation of the visor will orient the OS in the desired orientation and trap the boss on the OS at

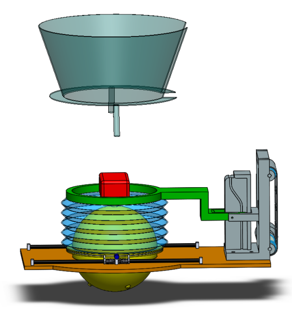

Figure 27. Concept 3 Cone Ejection Phase

the most concave locations on the two visors. Unlike concept 2, the steps for capture and orientation are distinct and hence can be separately tested. The capture volume is similar to that in concept 2 and is thus larger than in concept 1. This concept also makes minimal changes to the OS outer geometry, requiring only a small boss to protrude out of the sphere and a negative feature for the retention. It also ensures that the OS can be oriented to a unique orientation, to some tolerance, and not have the ambiguity of the two polar configurations as observed in concept 2.

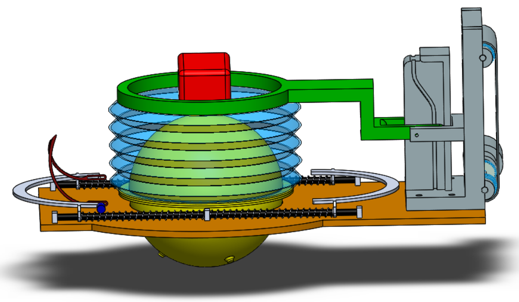

Figure 28. Concept 3 Visor Ejection Phase

However, this concept relies strongly on availability of clearance between the two BTC shells to incorporate the visor mechanism along with any BTC elements needed for the sealing process. The concept also is dependent on successful ejection of the visor mechanism for the BTC shells to close. Further, the shapes of the visors have to be carefully designed such that the boss on the OS can slide down to the most concave location on the visors. This has to be carefully designed to avoid any configurations where the boss can bind on the visor surfaces or any configurations in which the boss can get mechanically jammed between the visors. One concept for reducing the boss friction loads between the visors is to enable the boss to rotate about its axis, thereby providing opportunity for rolling and not just sliding.

8. CONCLUSIONS

In this paper, we have evaluated the current trade-space of concepts generated for both the individual aspects of capture and manipulation of the OS as well as concepts for the end-to-end system. We also present three integrated engineering concepts that integrate the different functional elements in a form consistent with the overall understanding of the system at this point in time. It is possible that a potential Mars Sample Return mission element may look different from the concepts presented here or may have a modified version of these concepts.

This work is an on-going research activity at NASA JPL and continues to evolve in accordance with changes in the potential NASA JPL Mars Sample Return mission requirements.

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10. REFERENCES

[1] Mattingly, R., Matousek, S., and Jordan, F., *Continuing Evolution of Mars Sample Return* 2004 IEEE Aerospace Conference Proceedings, Vol. 1, IEEE Publications, Piscataway, NJ, 2004, pp. 477–492.

[2] Mattingly, R., Matousek, S., and Jordan, F., *Mars Sample Return, Updated to a Groundbreaking Approach* 2003 IEEE Aerospace Conference Proceedings, Vol. 2, IEEE Publications, Piscataway, NJ, 2003, pp. 745–758.

[3] Mattingly, R., Matousek, S., and Gershman, R., *Mars Sample Return: Studies for a Fresh Look* 2002 IEEE Aerospace Conference Proceedings, Vol. 2, IEEE Publications, Piscataway, NJ, 2002, pp. 509–515.

[4] Oberto, R., *Mars Sample Return, a Concept Point Design by Team-X (JPL's Advanced Project Design Team),* 2002 IEEE Aerospace Conference Proceedings, Vol. 2, IEEE Publications, Piscataway, NJ, 2002, pp. 559–573.

[5] Kornfeld R. P., Parrish J. C., Sell S. (2007) *Mars Sample Return: Testing the Last Meter of Rendezvous and Sample Capture*, Journal of Spacecraft and Rockets, Vol. 44, No. 3, May–June 2007.

[6] Kumagai M and Ochiai T (2008) *Development of a robot balancing on a ball*. International conference on control, automation and systems, Seoul, 14–17 October, pp. 433–438.

[7] Hiltz M. et al. (2001) *Canadarm: 20 years of mission success through adaptation*, Proceeding of the 6th International Symposium on Artificial Intelligence and Robotics & Automation in Space: i-SAIRAS 2001, Canadian Space Agency, St-Hubert, Quebec, Canada, June 18-22, 2001.

[8] Karapetian, Polit-Casillas, Aaron, Soloway, Bezkrovny, Easter, Gershman, Hendry, Hirsch, Kulczycki, Lock, Le, Mukherjee, Oftadeh, Ohta, Parrish, Partansky, Sirota, Ravich, Rozek, Whetsel, Ziemer, *Mars ROCS – Mars Sample Return; Atelier 003*, JPL Atelier Report 2016

11. BIOGRAPHY

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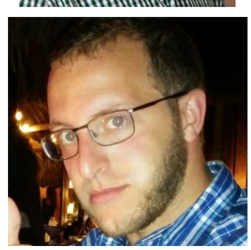

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